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The rotation of very low-mass stars and brown dwarfs

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Abstract. The evolution of angular momentum is a key to our understanding of star formation and stellar evolution. The rotational evolution of solar-mass stars is mostly controlled by magnetic interaction with the circumstellar disc and angular momentum loss through stellar winds. Major differences in the internal structure of very low-mass stars and brown dwarfs – they are believed to be fully convective throughout their lives, and thus should not operate a solar-type dynamo – may lead to major differences in the rotation and activity of these objects.

Here, we report on observational studies to understand the rotational evolution of the very low-mass stars and brown dwarfs.

Keywords. stars: activity, stars: evolution, stars: formation, stars: low-mass, brown dwarfs, stars: magnetic fields, stars: rotation

1. Introduction

The study of stellar rotation during the pre-main sequence (PMS) and the main sequence (MS) phase has provided us with many new insights into their formation and evolution (Bodenheimer 1995, Bouvier et al. 1997, Stassun & Terndrup 2003, Herbst et al. 2007). The so-called angular momentum problem of star formation asks how the specific angular momentum (angular momentum / mass) of dense molecular cloud cores, from which low-mass stars form, gets reduced by 5 – 6 orders of magnitude compared to what is left in solar-type stars on the zero-age main sequence (ZAMS). An additional 1 – 2 orders of magnitude is lost from the ZAMS to the age of the Sun ($\sim$ 5 Gyr).

At the early formation stages, magnetic torques between the collapsing cloud core and the surrounding interstellar medium, the deposition of a large amount of angular momentum into the orbital motion of a circumstellar disc, a planetary system, and/or a binary star system play important roles. It is known that solar-mass stars already in their T Tauri phase rotate slowly, although they are still accreting matter from their disc. Magnetic coupling between the star and its circumstellar disc, and the consequent removal of angular momentum in a highly collimated bipolar jet are considered to be the agent for this rotational braking (e.g., Camenzind 1990, Königl 1991, Shu et al. 1994, Matt & Pudritz 2005). After the cessation of accretion and the following dispersal of the disc this braking mechanism obviously comes to an end, and the rotation is observed to accelerate as the PMS stars contract towards the ZAMS. On the main sequence then, the rotation rates of solar-mass stars decrease again, because now angular momentum loss through stellar winds takes over as the dominant process.

The rotation of stars can either be measured spectroscopically from the line-broadening of photospheric spectral lines, or it can be derived from periodic variability in the light curves of stars seen in photometric time series observations. While the spectroscopic method suffers from projection effects – the inclination angle of the rotation axis with

respect to our line of sight is unknown – the photometric method allows us to determine the rotation period with high precision and independent of inclination angle.

Whereas a large amount of rotation periods are now available in the literature for low-mass stars in clusters younger than about 3 Myr (ONC: Herbst et al. 2001, Herbst et al. 2002; NGC2264: Lamm 2003, Lamm et al. 2004), and most recently in the much older M34: Irwin et al. (2006) and NGC2516: Irwin et al. (2007), not much is known about the early evolution of very low-mass (VLM) stars and brown dwarfs up to the age of a few Gyr, when they are found as field object in the solar neighbourhood (Bailer-Jones & Mundt 2001, Clarke et al. 2002). This has lead us to initiate a programme to study the rotation periods of the VLM stars and brown dwarfs, and to compare them to solar-mass stars as well as to evolutionary models. For our monitoring programme we decided to follow the photometric time series approach to obtain precise rotation periods.

In this text, we first present our results on rotation rates and variability of the sources in Section 2. The observed rotation rates are then compared to various models of rotational evolution in Section 3. In Section 4 we discuss some first attempts to characterise the spots on VLM objects, followed by some comments about accretion and time variability in these objects in Section 5. Finally, Section 6 contains our conclusions.

2. Rotation and variability of VLM objects

In the course of our ongoing monitoring programme, we have so far created a database of rotation periods for 23 VLM objects in the cluster around sigma Ori (Scholz & Eislöffel 2004a), for 30 in the field around epsilon Ori (Scholz & Eislöffel 2005), which are belonging to the Ori OBIb association, and for 9 objects in the Pleiades open cluster (Scholz & Eislöffel 2004b). At ages of about 3, 5, and 125 Myr these three groups of VLM objects form an age sequence that allows us some insights into a relevant part of their PMS evolution.

In general, the observed periodic variability in the light curves of our VLM targets is attributed to surface features, which are asymmetrically distributed on the surface and are co-rotating with the objects. Such surface features may arise from dust condensations in the form of "clouds", or from magnetic activity in the form of cool "spots". Because of their youth all our objects have surface temperatures $T_{\rm eff} > 2700$ K (Baraffe et al. 1998), which corresponds to spectral types earlier than M8. These temperatures are higher than the dust condensation limits, so that we are most likely observing cool, magnetically induced spots.

It is interesting to compare the mass dependence of the rotation periods for the VLM and solar-mass objects. For the Pleiades, we find that their period distributions are different. While periods of up to ten days are known for the solar-mass objects, Fig. 1 shows that among the VLM objects we are lacking members with rotation periods of more than about two days. Although our photometric time series extends over a time span of 18 days, slow rotators might have been missed among the VLM objects, if their spot patterns evolved on a much shorter time scale, or if they did not show any significant spots.

These possibilities can be checked by converting the spectroscopically derived lower limits for rotational velocities from Terndrup et al. (1999) and references therein into upper limits for the rotation periods of the VLM objects using the radii from the models by Chabrier & Baraffe (1997). Such spectroscopically derived rotational velocities should not be affected by the evolution of spot patterns on the objects. The derived upper period limits are shown in Fig. 1 as a solid line. With a single exception, all our data points fall below this line. Hence, they are in good agreement with the spectroscopic

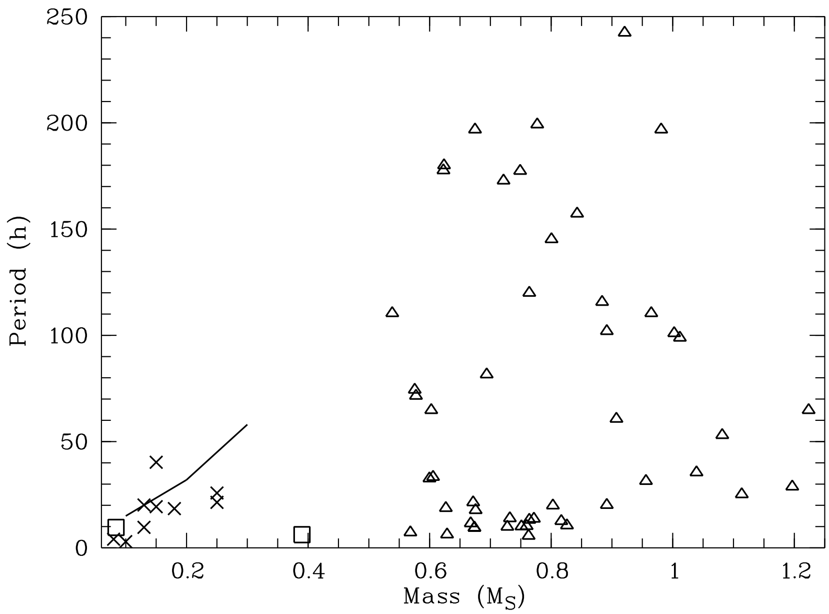

Figure 1. Rotation periods versus mass in the Pleiades. Our rotation periods for VLM objects are shown as crosses. Triangles mark the periods for solar-mass stars from the Open Cluster Database. The two squares show periods from Terndrup et al. (1999) The solid line marks the upper limit to the observed $v \sin i$ values of Terndrup et al. (2000).

rotation velocities. Both complementary data sets indicate the absence of slow rotators among the VLM objects. Looking at them in detail, they even show a trend towards faster rotation even within the VLM regime from higher to lower masses. Such a trend is also seen in our data of the epsilon Ori cluster, and in the Orion Nebula Cluster data by Herbst et al. (2001).

3. Rotational evolution of VLM objects

We now want to combine the periods for all three clusters that we observed, namely sigma Ori (Scholz & Eislöffel 2004a), epsilon Ori (Scholz & Eislöffel 2005), and the Pleiades (Scholz & Eislöffel 2004b), to try to reproduce their period distributions with simple models. These models should include the essential physics of star formation and evolution that we described in Section 1. A practical way of doing this is to project the period distribution for sigma Ori forward in time and then compare the model predictions with our observations for epsilon Ori and the Pleiades.

It is obvious, that the hydrostatic contraction of the newly formed VLM objects has to be taken into account in a first step. Changes in their internal structure may be negligible for these fully convective objects (Sills et al. 2000). Then, their rotation periods should evolve from the initial rotation period at the age of sigma Ori strictly following the evolution of the radii (which were taken from the models by Chabrier & Baraffe 1997). Therefore, the rotation accelerates, and should only level out for ages older than the Pleiades, when the objects have settled (dotted lines in Fig. 2). This model, however, is obviously in conflict with the observed Pleiades rotation periods. Half of the sigma Ori objects would get accelerated to rotation periods below the fastest ones observed in the Pleiades of about 3 h. Furthermore, even the slowest rotators in sigma Ori would get

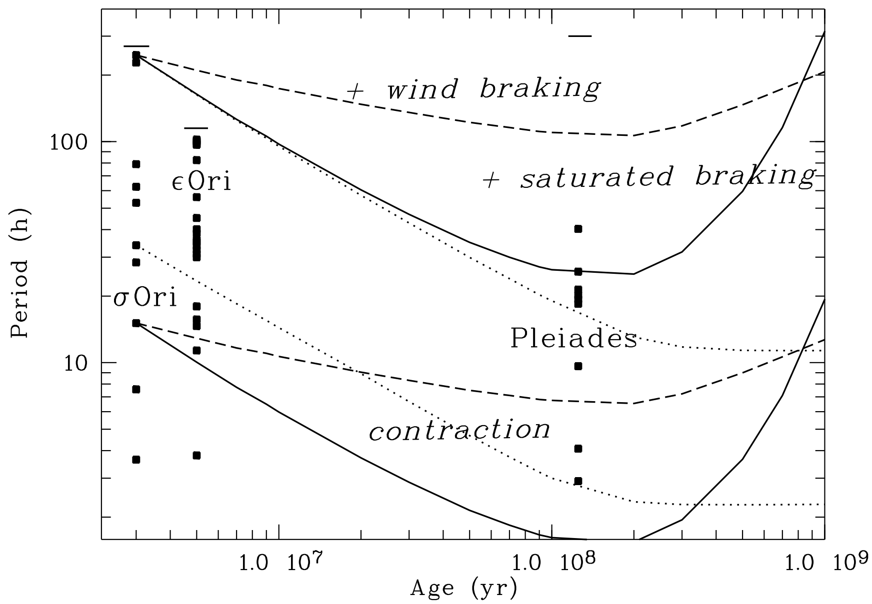

Figure 2. Rotational evolution of VLM objects. The dotted lines show the evolution of the rotation periods for a couple of objects for a model of hydrostatic contraction only. A model with additional Skumanich type braking through stellar winds is shown as dashed lines, and models that use a saturated wind braking instead are shown as solid lines.

spun up to velocities much faster than the slower rotators in the Pleiades, which would remain unexplained then. This teaches us that significant rotational braking must occur until the objects reach the age of the Pleiades, because it is clear that the sigma Ori VLM objects will undergo a significant contraction process.

In a second model we now add a Skumanich type braking through stellar winds, as it is seen in solar-type MS stars (Skumanich 1972). This wind braking increases the rotation periods $\sim t^{1/2}$, as shown by the dashed lines in Fig. 2. However, following this model some of the sigma Ori slow rotators would get braked far to strongly. For a Skumanich type wind braking they would become clearly slower rotators than are observed in the Pleiades (see also above). A possible solution to this problem is to assume that even the slowest sigma Ori rotators seem to rotate so fast, that they are beyond the saturation limit of stellar winds (Chaboyer et al. 1995, Terndrup et al. 2000, Barnes 2003). In this saturated regime, angular momentum loss is assumed to depend only linearly on angular rotational velocity, and therefore rotation periods increase exponentially with time. The solid lines in Fig. 2 show a model of contraction and saturated wind braking. The period evolution of this model is the most consistent with our data.

It is interesting to explore if disc-locking – as an angular momentum regulator active only at very young ages – may also play a role for the evolution of rotation periods. The sigma Ori cluster would be young enough for this process to play a role, and indeed we found evidence that some of our objects in this cluster may possess an accretion disc. Therefore, we investigate a scenario in which disc-locking is active for an age up to 5 Myr, typical for the occurrence of accretion discs in solar-mass stars. During this time rotation periods would remain constant. This disc-locking scenario we combined with the saturated wind braking, with an adapted spin-down time scale. In Fig. 3 dashed lines are shown for two objects following this model, together with the pure saturated wind

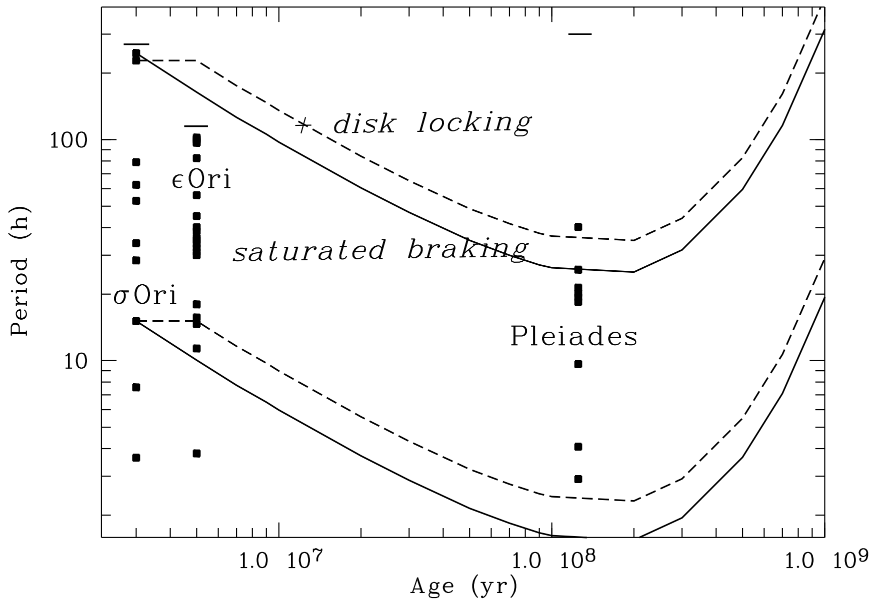

Figure 3. Rotational evolution of VLM objects. The evolution of the rotation periods for a couple of objects for a model with hydrostatic contraction and saturated wind braking are shown as solid lines, as in Fig. 2, while a model with added disc-locking up to an age of 5 Myr is shown as dashed lines.

braking model discussed above (the solid lines, as in Fig. 2). The period evolution for both models is nearly indistinguishable. It turns out that from our currently available rotation periods for these three clusters, strong constraints for or against disc-locking on VLM objects cannot yet be placed.

4. The spots of VLM objects

Not much is known about the properties of the spots on VLM stars and brown dwarfs. First clues on the physical properties of the spots may be obtained from multi-filter time series observations. In principle, they allow us to measure the variation amplitudes in the light curves at various wavelengths, and from this information to derive the (asymmetric part of the) spot filling factor and the temperature difference between the spots and the average atmosphere – although this method is not capable of delivering unique solutions.

Therefore, in parallel to a photometric time series campaign of the Pleiades in the I-band, we measures in the J- and H-band simultaneously on a second telescope (Scholz et al. 2005). Only one VLM star (BPL 129) showed a period in all three wavelength bands at a signal-to-noise high enough so that we could derive spot properties. For several other Pleiades VLM stars and brown dwarfs only limits could be placed.

The best agreement between the observations and a one-spot model is reached for a cool spot with a temperature 18 to 31% below the average photospheric temperature and a filling factor of $4 - 5\%$ (see Fig. 4). These results indicate that spots on VLM stars may have a similar temperature contrast between spot and average atmosphere, but a rather low spot filling factor compared to solar-mass stars. This might be a consequence of a change in the dynamo from a solar-type shell dynamo to a small-scale turbulent dynamo in these fully convective stars.

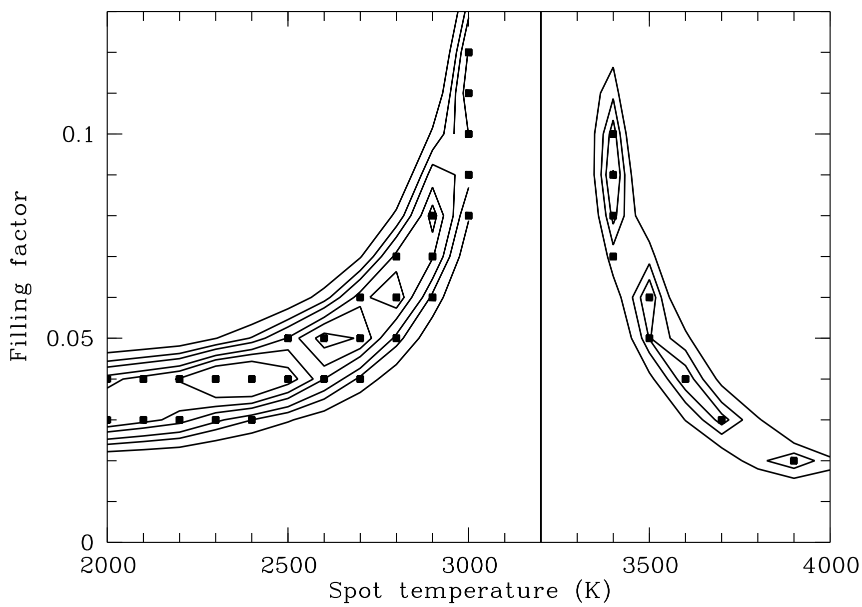

Figure 4. Contour plot for the χ^2 values from the comparison between observed and simulated spot amplitudes in the Pleiades VLM star BPL 129. Contour lines start at χ^2 =3.0 and are plotted for χ^2 =3.0, 2.0, 1.5, 1.0, 0.75, 0.5, indicating increasing quality of the fit. Filled squares show all combinations of spot temperature and filling factor which would produce amplitudes within the error bars of our observations. The vertical solid line indicates the photospheric temperature of BPL 129. Note that the hot spot solutions on the right side never reach to the 4th contour line, and χ^2 is larger than 0.9 everywhere. They are thus significantly worse than the cool spot solutions on the left side. (One data point with $\chi^2 = 0.92$ at $T_S = 3300$ K and $f = 19\%$ is not shown in the figure.)

5. Accretion and time variability

In the course of our data analysis we noted that a few of the VLM objects in the two Orion regions show large amplitudes of up to 0.6 mag (see Fig. 5). These variations are, however, much of an irregular character. Because of the large amplitudes, it is most likely that they result from hot spots originating from accretion of circumstellar disc matter onto the object surface (see also Fernández & Eiroa 1996). Emission lines in Hα, the far-red Calcium triplet, and – in some cases – even forbidden emission lines of [OI]$\lambda\lambda$6300,6363 and [SII]]$\lambda\lambda$6716,6731 are seen in optical spectra that we obtained of some of these objects in sigma Ori. These spectra thus show signatures typical of accretion, much like those of classical T Tauri stars. In addition, in a near-infrared colour-colour-diagram the high-amplitude variables mostly lie in the reddening path or even redward of it, thus showing near-infrared excess emission that is usually taken as evidence for a circumstellar disc. With their photometric variability, spectral accretion signatures, and indications for near-infrared excess emission from discs appear to be the low-mass and substellar counterparts to solar-mass T Tauri stars.

It is interesting that the high-amplitude T Tauri analogs on average are slower rotators than their low-amplitude non-accreting siblings. A similar tendency that brown dwarfs with discs seem to rotate more slowly is also seen in spectroscopic measurements of v sin i by Mohanty et al. (2005). It thus seems that even in the substellar regime a connection between accretion and rotation exist, possibly implying rotational braking due to interaction between object and disc (Scholz & Eislöffel 2004a).

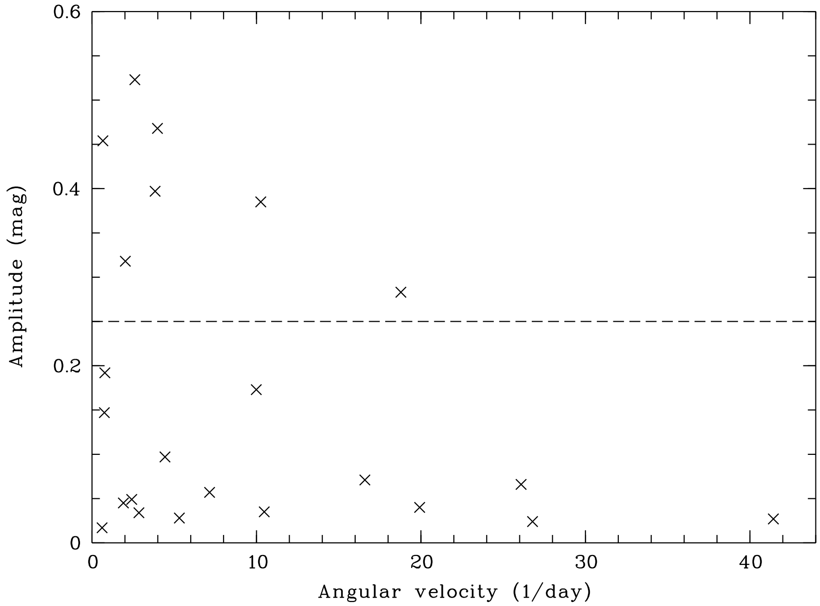

Figure 5. Angular velocity versus amplitude of VLM stars and brown dwarfs in the sigma Ori cluster. The dashed line delineates the separation between low-amplitude and high-amplitude objects. The high-amplitude objects are mostly active accretors, and on average rotate slower that the non-accreting low-amplitude objects.

6. Conclusions

We report results from our ongoing photometric monitoring of VLM objects in the clusters around sigma Ori, epsilon Ori, and the Pleiades, and our first attempts to model their rotational evolution.

It is very likely that the observed periodic variability of many VLM objects originates from magnetically induced cool spots on the surfaces of the objects. In particular in the Pleiades, variation amplitudes in VLM objects indicate either less asymmetric spot distribution, smaller relative spotted area, or lower contrast between spots and average photosphere than in solar-mass stars. VLM objects show shorter rotation periods with decreasing mass. This effect is observed already at the youngest ages, and therefore should have its origin in the earliest phases of their evolution.

Combining the rotation periods for all our objects, we find that their evolution does not follow hydrostatic contraction alone. Some kind of braking mechanism, e.g. wind braking similar to the one observed in solar-mass stars, is required as well. Such a wind braking is intimately connected to stellar activity and magnetic dynamo action (Schatzman 1962). Nonetheless, since all the investigated VLM objects are expected to be fully convective, they should not be able to sustain a solar-type large-scale dynamo, which is at the heart of the Skumanich type angular momentum loss of solar-mass stars. In fact, our modelling shows that such a Skumanich type wind braking cannot explain our data, while saturated angular momentum loss following an exponential braking law can. This and the observed small photometric amplitudes may advocate a change in the magnetic field generation in the VLM regime. The exact type of dynamo operating in VLM objects is unclear. In principle, observations of rotation bear great potential to distinguish between the various scenarios for such dynamos (e.g., Durney et al. 1993, Chabrier & Küker 2006). However,

consistent theoretical models that provide predictions for rotational braking in the very low-mass regime and thus rigorous testing against the observations, are not yet available.

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